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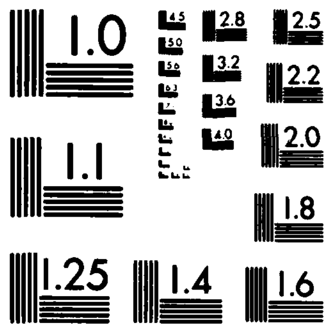


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AGARD ADVISORY REPORT No. 189

# Technical Evaluation Report on the Fluid Dynamics Panel Specialists' Meeting on Prediction of Aerodynamic Loads on Rotorcraft



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AGARD Advisory Report No.189

# TECHNICAL EVALUATION REPORT

**on the**

# FLUID DYNAMICS PANEL SPECIALISTS' MEETING

**on**

# PREDICTION OF AERODYNAMIC LOADS ON ROTORCRAFT

by

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The Proceedings of the AGARD Fluid Dynamics Panel Specialists' Meeting Prediction of Aerodynamic Loads on Rotorcraft, which was held in London, United Kingdom, on 17–18 May 1982, are published as AGARD CP 334, September 1982.

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# A TECHNICAL EVALUATION REPORT FOR THE SPECIALISTS MEETING ON "PREDICTION OF AERODYNAMIC LOADS ON ROTORCRAFT" (LONDON, ENGLAND 17 - 18 May 1982)

by

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## 1. INTRODUCTION

The aerodynamic loads on rotorcraft are unique to these aircraft. Because of the rotary motion of the rotor blades and their translation through the air, the flow field as seen by an observer in the fuselage is essentially unsteady and generally periodic. The aerodynamic phenomena that result include subsonic yawed flow, transonic flow, separation and reattachment, and 3-D flows. While operating in this environment, the rotor blade elements generate the forces necessary to provide aircraft lift, propulsive thrust, and control. As this lift is generated, both shed and trailing vorticity is left in the wake. A mutual interaction takes place between this rotor flow and the flow about the fuselage.

These non-steady aerodynamic actions induce periodic loads in the structure with resulting blade and fuselage dynamic response, structural fatigue, and vibration. They lead to significant restrictions on aircraft performance and control. The blade and aircraft motions in turn can modify the blade aerodynamics so that the resulting wake is the instantaneous synthesis of all the effects: aerodynamic, dynamic and mutual interference.

These actions occur simultaneously. A proper model would include all of them. It has not been possible to produce so extensive a model as this picture would demand. Analytical methods used to describe the loads have progressed slowly. They reached a relative maturity which was reviewed in a prior AGARD conference on rotor loads in 1973 (20). High levels of sophistication were evident in several papers relative to the analysis of structural response. The level of aerodynamics used throughout the community seemed to be relatively uneven, with some organizations including non-steady effects, separation, yawed flow, and non-uniform wakes while other groups used simple uniform wake models and did not account for yaw. Since that 1973 meeting advances have been made in computer modeling techniques, experimental facilities and methods. Many studies and tests have been conducted on airfoils, non-steady flows and rotor wakes. Rotorcraft loads programs have been upgraded and expanded.

The theme of this 1982 Specialist's Meeting arose from both the continuing need to provide improved prediction techniques for rotorcraft and the recognition of the growth in capability and understanding gained over the past decade. The primary theme was expressed in the announcement as: "the prediction and experimental verification of the steady and unsteady aerodynamic forces on the rotors of modern helicopters and related devices".

The symposium held to address this them was arranged by the Fluid Dynamics Panel of AGARD. It was entitled "Prediction of Aerodynamic Loads on Rotorcraft" and held at the Church House London, United Kingdom, 17-18 May 1982. Four half-day session were held and a total of 19 papers were presented. The sessions covered the following topics

- Rotor Blade Aerodynamic Characteristics
- Wakes and Aerodynamic Interference Effects of Rotorcraft and Wind Turbines
- Rotor Airload Prediction Programs
- Experimental Correlations and Verifications

## 2. TECHNICAL DISCUSSIONS

The opening speaker set the tone for the following two days of discussion. He made the point that helicopter loads depend upon helicopter aerodynamics and that helicopter aerodynamics has grown into its own field in its own right. Since the rotor operates with separated flow in a complex flow field, the determination of loads presents a significant challenge. He stated that specific emphasis should be placed on obtaining experimental data with which to verify the analytical methods which are becoming available. He suggested that future work should be directed towards:

- extending the analytical methods into manuevering flight
- determining the actual limits to helicopter flight
- considering the 3-D effects on rotors more extensively
- moving away from purely empirical models of separation
- integrating structural and aerodynamics in the design phase
- improving fuselage, aerodynamic drag and download predictions
- developing adequate tail rotor aerodynamics through all phases of its operation

He posed the purpose of the meeting succinctly by asking two questions. What is the capability to predict airloads? What is the accuracy of the prediction made? He expressed the view that classical methods were inadequate to meet the design needs for the forthcoming generation of helicopters, and that the older approaches using 2-D steady airfoil data, uniform downwash or prescribed wakes, rigid blade dynamics and chart or table methods would have to be upgraded. The complete rotor rather than individual blades

would have to be considered including blade stall and reattachment, transonic tip (3-D) effects, realistic wake models, coupling of wake, blade and fuselage aerodynamics, and improved computational and analytical modeling of these phenomena. The speaker concluded by saying that significant benefits could be obtained by this improved modeling and would include more reliable predictions of performance, vibratory stresses, dynamic response, vibration and acoustic signature.

## 2.1 ROTOR BLADE AERODYNAMIC CHARACTERISTICS

The emphasis of the opening session focused predominantely on airfoils and rotor blade tip aerodynamics.

The intial paper addressed advanced rotors (1). The projected need for the helicopter to operate routinely at speeds beyond 200 knots with good fuel efficiency requires high performance rotors. The view was expressed that improvements in rotors would be achieved by a mixture of test and analysis. Analytical methods used to date in rotor aerodynamics have included:

- 2-D Airfoil design methods including potential flow/boundary layer interactions, viscous-transonic effects, and separated flow
- Rotor operation in hover using lifting line and lifting surface methods with prescribed wake and improved wake models (no details of the wake model were presented).
- Rotor operation in forward flight using lifting line methods with non-uniform downwash, 2-D airfoil data, 3-D effects, unsteady aerodynamics, and upwash interference effects. Lifting surface methods are being studied.

The paper then traced the evolution of the VR airfoils starting from the NACA 0011, through a modified 23010, the VR-7 and VR-8 to the more recent VR-12, VR-15 family. A gain in rotor L/D of the order of 20% at a speed of 140 knots was predicted for the VR-12, VR-15, relative to the earlier VR-7, VR-8 series. The paper also reviewed work on rotor blade planform geometry in the tip area. Tip shapes had been studied which can account for varying Mach number along the outer portion of the blade. A reduction in local Mach number effects could be expected from suitable blade tip shaping.

This paper advanced the view that some of the greatest gains arising from rotor aerodynamic analysis have come in the ability to better define the environment for airfoils which has in turn led to improved airfoils. It also pointed out that in the past significant gains in rotor technology have come from extensive tests of helicopter and rotor models in wind tunnels. One of the dominant conclusions drawn that "analysis and wind tunnel tests will have to complement each other more closely," raises the fundamental concern, "Just how good is the analysis?"

The second paper dealt with dynamic stall (2). A model based upon both the Wagner indicial function and Kirchhoff *separation theory* was presented. Modeled were lift delay with dynamic stall, influence of Mach number and separation on the normal force, pitching moment and the drag coefficient. A criterion based upon shock pressure rise ratio was presented which would predict the point of the pitching moment break. The effect of trailing edge separation on normal force and pitching moment was analyzed using the Kirchhoff theory which relates $C_L$ to the separation point on the airfoil. Leading edge or shock induced separation was modeled using a vortex moving across the surface. In this model, the strength and initial location of the shed vortex was based upon the shift in separation point as obtained using the Kirchhoff approach.

The correlation achieved between this empirically based model and measured normal force and pitching moment coefficients of a NACA 0012 airfoil appeared to be excellent. The unique feature of the approach was the use of the separation point as an independent degree of freedom. Though the method seems quite useful, further verification of its validity should be undertaken by applying the method to airfoils for which an adequate data base exists. It should be noted that this paper restricts itself to the separation phase of the retreating blade stall problem.

The next paper reviewed work on airfoils, tip sweep and flow measurements (3). The airfoils were based upon a new section, the OA 209. They were tailored to meet the varying requirements which exist for a rotor blade. For hovering flight, a lift coefficient of 0.6 at a Mach number of 0.6 was considered to be desirable. In forward flight the retreating blade would require a high lift coefficient at a low section Mach number while the advancing blade tip would require a high drag divergence Mach number at low lift coefficient.

Model rotors had been fabricated using the OA series of airfoils and had been tested in hover. Results with OA-207 and OA-209 section indicated superior performance relative to the NACA 0012 standard configuration. Wind tunnel tests of the new airfoils showed significant gains for the model rotors using blades that had thick OA airfoils inboard and thin 6% OA airfoils near the tip.

The paper reported on studies of tip sweep. Using the method of Caradonna, results indicated that the regions of supersonic flow on the surface of non-lifting blades could be significantly reduced by properly shaping the sweep angle. Model rotors using the tip sweep analyzed were tested in the S-2 tunnel at Chalais-Meudon. A reduction in power of the order of 5-8% at high flight speeds resulted when the swept tip blades were used in place of blades having rectangular tips.

Measurements of rotor wakes were also reported. Using a model rotor, tip vortex positions and inflow velocities were obtained in hover and downwash velocities were obtained below the 90° azumuth position in forward flight.

The next paper dealt primarily with the analysis of unsteady and 3-D effects of flows around rotor blade tips (4). Presented were results of using fixed wing computational methods on the outer 25% of a rotor blade with the goal of improving the representation of the tip. The results of the analysis were compared to the model rotor test data presented by Caradonna and Philippe in reference 22 and agreement obtained for chordwise Cp for a range of advance ratios was quite good. Comparison of local values of Cp, at x/c = 0.3 for example, on the advancing blade were in general agreement, but the calculated position of of the collapse of the pressure peak after the shock lagged significantly behind the measured position. It was particularly encouraging to see the continuing adapatation of fixed wing analytical techniques to the problems of helicopter rotor analysis.

Viewed in perspective, this session on blade aerodynamic characteristics revealed that significant advances have been made in the development of new airfoils, in the analysis and test of tip shapes, and in the analysis of transonic, non-steady and separated flows. *None of the analyses attempted, however, to*

view blade geometry and analysis within the more complex induced rotor flow field. Although some work was reported on the effect of tip votex impingement on span loading, the influence of the curvilinear flow field induced by the individual vortices on blade pressure distribution, stall, profile shape and blade shape was not directly addressed. The effects of compressibility in the wakes and vortex interaction effects in the wake on the local flows at the blade were not addressed. It also would seem necessary to consider testing airfoils in environments which more completely simulate this non-steady curvilinear near wake.

## 2.2 WAKES AND AERODYNAMIC INTERFERENCE EFFECTS OF ROTORCRAFT AND WIND TURBINES

The first two papers of this session dealt with the computation of aerodynamic loads on wind turbines. The first paper reviewed the analytical efforts that have been made to describe the aerodynamics of wind turbines with tip vanes (5). The acceleration potential method was used for the wind turbine and was an application of the method developed by Van Holten for helicopter rotors. Its use results in asymptotic solutions with near field, far field, and common terms. The method eliminates discontinuities in the flow field except for pressure discontinuity on the solid boundaries of the field. It involves the integration of the acceleration of the fluid particles along an assumed straight, unperturbed trajectory, and is essentially a small perturbation method. Though it is believed to be a potentially very useful method, it may be limited to situations where no large variations are taking place. Thus in regions where vortex-blade/surface interactions are taking place this model may not be able to represent the details of the flow adequately. The tip vane wind turbine concept is heavily dependent on flow field-vane interactions and hence near field actions are important. Because of this, it is considered vital that detailed flow measurement be taken, and then the theory for the turbine-tip vane configuration could be compared with data.

The next paper considered load calculations for two bladed windmills (6). It utilized momentum-strip theory methods modified by empirical data to account for operation in the turbulent flow states and included the effects of vertical wind shear, tower disturbance and cross flow. Using the results of prior studies, a preliminary design method was developed to account for these inputs. The entire rotor assembly was assumed to be rigid. Detailed review of the paper did not reveal whether a flapping or teetering hinge had been incorporated. Blade flexibility always exists and even with the absence of a flapping hinge, dynamic blade motion will result. Such motion would lead to changes in local angle of attack-distribution and thus in the loads calculated.

The next two papers dealt with helicopter wakes in hover. The first of these papers compared a theoretical free wake model with experimental results (7). The analytical approach started with a prescribed wake approach to locate the trailing vortex structure, then used the Biot-Savart law to get the induced velocity field and the new vortex positions in the wake. The process was repeated until the wake converged. It was found that the vortex filament position in the wake was quite sensitive to the assumed size of the vortex core.

The tests which were conducted utilized a 1.5 meter diameter rotor of 0.05m chord and tip speed of 107 m/s. Six different rotors were tested with selected twist distribution, airfoils and tip shape. Velocity measurements were made using both hot wire and laser velocimeter techniques. The position of the tip vortices were mapped using both visualization and velocity measurements.

The agreement between theory and test for vortex position was quite good for the case of rectangular tip rotors. This could be expected since almost all prior work on the prescribed wake theories have been based on rotors with rectangular or nearly rectangular tips and with linear blade twist. The hot wire and visualization data were in good agreement. In the case of a model rotor with non-linear twist the comparison of analytical and experimental vortex position was not clearly as good as for the rectangular tip case. No comparison was made for the swept tip cases since the analysis was not yet complete, but the data indicated reduced radial contraction of the wake for the swept tip configuration. Comparisons made for the tapered tip case showed excellent correlation between the relaxed wake model described above and the test results.

Data were also presented for vertical velocity at specific azimuth positions near the blade tip. The agreement between data and analysis for vertical velocity was quite good for the rectangular blade, but significant discrepancies existed between the calculated distribution and measured data for the tapered tip.

It is apparent from a study of the paper that good correlation between theoretical results and test data can be achieved in the cases of rectangular or nearly rectangular blades with regular twist. It is also evident that when significant deviations from these baseline geometries occur, good correlation is not yet achievable with any degree of confidence with the lifting line-prescribed or relaxed-free wake methods as presented.

The next paper presented an extension to the prescribed wake methods currently in use for hovering performance analysis (8). The method had evolved from prescribed wake models in which the wake is described in terms of the axial and settling velocities and circulation coupled wake models in which the settling rates become functions of the tip vortex strength. In this new model, a velocity coupled hover wake model, the radial and axial vortex positions are related to characteristic velocities in the wake. The radial contraction parameter $\lambda_1$ in the radial position equation

$$r/R = A + (1-A)e^{-\lambda_1\Psi}$$

is based upon a combination of lateral (radial) velocity induced by the near field of the blade above the first trailed vortex and the radial flow velocity induced by the discrete tip vortices trailed in the wake. An empirical correlation of $\lambda_1$ with a linear combination of these two induced velocities was achieved.

The settling rate paramenter, $k_1$, (the initial rate till next blade passage) was set to be equal to a settling rate due to the mean inflow less an interference velocity rate due to the velocity induced by the initial tip vortex spiral up to the next blade passage. Then $k_2$, the settling rate after blade passage, was set equal to the settling rate due to mean inflow rate plus the same interference velocity. The mean inflow rate in the case of a constant chord, constant twist rotor was found to correlate well with the momentum value. Specific emphasis was then placed upon the problem of obtaining the mean inflow settling rates. A vortex cylinder model was used which incorporated the blade tip circulation, $k_2$, the radial position of the vortex at first passage and a wake cylinder whose length is described by an empirical function of the vortex position at next blade passage. Correlation of the model with existing data for one, two, and four bladed model rotors was made. The correlations were indeed good for the cases presented. The model was then extended to cover climb performance. Correlation with data obtained in sidewards flight of a model tail rotor also showed acceptable agreement.

Though correlation was achieved, it is believed to be imperative that other selected rotor

configurations be analyzed with this method and that concurrently, wake geometries for these rotors to be determined experimentally. If good correlation between prediction and test results is obtained then greater confidence in the model would be warranted. It is possible that some of the variables found to be useful in correlating the data would have physical significance as the authors imply, but this conclusion awaits more complete analyses starting from first principles.

The next paper reviewed three areas of aerodynamic interference which exist in helicopters; blade-to-blade vortex interaction, fuselage flow-rotor interaction, and fuselage-hub wake effects on the tail (9). Calculations were made of the tip vortex-following blade interaction. The vortex interactions could be seen as pulses in the thrust traces at specific spanwise locations. As would be anticipated, descent in foward flight led to much higher and more persistent pulses. No direct comparisons were made with flight data for these cases. Figures were also presented of the harmonic content of the local blade section thrust values obtained from flight test from a BO-105 helicopter. In descent and transient flare-to-land, significant levels of higher content were found as would be expected.

The paper then discussed the influence of the flow about the fuselage on the operation of the rotor. As is well known, the flow over the front of the fuselage causes an upflow at the rotor and increased angles of attack in the forward part of the disk. The down flow over the aft fuselage causes a decrease in angles of attack in the rear of the disk. Calculations were made of this effect and the results indicated increased harmonic content of the lift forces. This action in turn would increase the higher harmonic inputs to the fuselage and be the source for the high vibrations that have been found with helicopters where the fuselage-rotor clearance is small.

The interference at the tail due to aft fuselage separation and hub wake was considered both analytically and experimentally. A separated flow model was used to study the flow field at tail of the BK-117 helicopter. Wind tunnel tests were run to measure the effects of hub wake on the flow in the tail area. A significant velocity defect was found whose position moved from below the tail plane to above it as the flight path changed from climb to level flight to descent. Measurements of the local unsteady effects in the tail area revealed considerable high frequency content in both flow angle and dynamic pressure. Such unsteady effects were related to fuselage vibration and tail shake. Improvements to both tail boom moment and tail plane loads were shown to occur when a hub cap was used.

The paper presented a good overview of work being done in areas of mutual interference. It served to emphasize the considerable difficulty facing the aerodynamicist. Not only must he be able to determine the flow field in steady hovering and forward flight, but he must also be able to provide analytical methods for a host of other flight conditions and flow conditions. It is considered unfortunate, however, that only limited comparisons were presented between theory and experiment.

The next paper proposed to discuss possible interference efforts of the rotor-fuselage combination on the internal aerodynamics of the engine (10). The paper presented a qualitative description of the whole range of helicopter aerodynamics and dynamic phenomena. Reviewed in a very general fashion were the thrust capabilities of rotors, rotor torque analysis, time histories of loads, and elements of compressor stall. Little specific discussion was given. No analytical methods or results were given nor were test results presented. Interference of rotor-fuselage flows with the internal aerodynamics of the engine installation and the engine itself would seem to be a very important issue. Interference could influence plenum design, pressure recovery, flow stability, icing, foreign object injection and momentum loss and spillage. It is regretted that subjects such as these were not treated or were covered only in a superficial way.

## 2.3 ROTOR AIRLOADS PREDICTION PROGRAMS

The papers in this section included a pragmatic means of airloads analysis, a discussion of the non-linearities of stall, a general dynamic analysis framework, an extensive review of current analytical techniques in the U.S. and the methodology used in the next generation of rotorcraft modeling.

The first paper reviewed the evolution of a practical method of rotorcraft loads prediction (11). Starting with a wake modelled with a series of ring vortices spaced along an assumed momentum wake, the model was modified to set better blade-wake intersection in the horizontal plane. The wake was then modified to include the effect of the fuselage. The flow about the nose of the fuselage was represented by a single point source so chosen to approximately match the results obtained from a panel method. Next, the model was modified to account for near wake effects by using a series of half rings springing from various radial positions on the blades. The local circulation was then calculated based upon the resultant flow at each blade segment. Comparisons made with flatwise bending data obtained from flight tests of a Puma helicopter indicated acceptable correlation.

The stated goal for the work was to produce a useful prediction method with low computer run time. The simplicity and low run time were achieved by use of a prescribed geometry which allowed the flows to be determined using elliptic integrals rather than requiring extensive numerical solution. The intriguing simplicity and potential pra :ality of the method commends it. Because the method does not attempt to model the details of the voı. x position precisely it would be expected that the method would most useful at higher advance ratios where the vortex-blade interactions will not be critical. At lower ratios and in manuevers, however, strong blade vortex interactions are more likely and a relatively simple model of the type presented may not be adequate to represent the flow.

In the next paper an extensive analytical approach was taken in the development of a loads prediction method (12). Aeroelastic coupling was included. The aerodynamic forces on the blades were based upon linearized aerodynamics in the first step and non-linear section characteristics were added in subsequent steps. The method considered compressible, 3-D, and non-steady effects on airfoil characteristics. Emphasis was placed upon operating in the stalled regime. The model was set up in a matrix formulation and the rotor airflow was modeled using the acceleration potential method. Two strip theory models were used to describe the separated flow region at the stall, a Boeing model and an ONERA model.

The predictions of the method were compared to data taken in wind tunnel tests and in flight test. Comparison of thrust around the azimuth of linear theory with data for was acceptable except near the tip where considerable disagreement was seen in the advancing blade region. In other regions comparisons based upon the harmonics of blade moment revealed reasonable agreement for the lower harmonics. Comparisons made with test data and nonlinear aerodynamics theory revealed improved correlations except in the region very close to the blade tip.

The method presented in the paper was quite comprehensive. It illustrated present day capability to model the non-linear region of airfoil behavior on rotors.

The next paper reviewed the development of a comprehensive global approach to rotorcraft dynamics (13). The authors stated that most dynamic analysis of helicopters concentrate on specific problems,

such as pitch-lag instability, ground resonance, or blade bending. The development of new, high performance helicopters with stringent requirements on life and vibration will require better prediction methods which would include the entire helicopter: airframe, components and the rotor. The approach taken started with a precise description of the individual elements and their constraints in a manner similar to finite element analysis. The equations of motion were set up in matrix form with either aerodynamic forces or imposed displacements as forcing functions.

The method as presented appeared to be very comprehensive. The aerodynamic model, at least at the stage presented was a relatively simple extension of momentum theory. Since the program was still under development and the paper of the nature of a progress report, no results of the analysis were given. The complexity of the problem being attacked and enormity of the program being developed requires that the program be verified carefully. It could also be expected that as confidence is built up in the model, more complete wake descriptions could be included.

In the next paper a broad overview of the state of the art in load prediction capability for rotors was presented (14). Based upon a survey of the U.S. technical community and the corporate experience of the authors, the paper discussed the changes in capability since the 1974 survey of Ormiston (21). The authors found that the most significant advances have occurred in structural and dynamic analysis. Structural redundancies were now being represented and substructure techniques allow the buildup to more complete representations. They also believed that although considerable research on sweep effects, 3-D flows at blade tips and dynamic stall have advanced understanding, little of the fundamental aerodynamics have as yet been incorporated in the working codes. Concern was expressed over the adequacy of wake models. Although fuselage rotor interference models are commonly used, it was not clear that they adequately represent the actual situation.

The authors expressed the view that the aerodynamics of rotors remained a critical area, and one in which added experimental and analytical work was needed. Specific emphasis should be placed on wake geometry, 3-D blade aerodynamics, and dynamic stall with sweep. The results should be put in a form that can be integrated readily into loads programs. Experimental efforts should proceed so that "- all elements of the problem: rotor wake geometry, rotor induced flow field, blade pressure, blade stresses and rotor loads, are measured simulataneously and in detail."

This paper was wide ranging yet presented an in depth look at the state-of-the-art in rotor loads. It indicated that significant progress has been made in the modeling of loads, yet it also pointed out the practical problems of continually updating and revising old computer simulations. It also made clear the necessity for careful, coordinated approaches to the next generation of prediction programs so that flexibility and control of the programs can be achieved.

The next paper presented the philosophy used in the development of the U.S. Army program for a comprehensive helicopter analysis program (2GCHAS) (15). Because prior programs had been developed for specific purposes such as stability and control, they could not be readily adapted to other uses. Often such programs had been found difficult to use by other than the code developer. To alleviate this difficulty, a project was initiated to develop a new, comprehensive rotary wing analysis program. In its development a full systems viewpoint was taken. Detailed evaluations of past helicopter analytical and experimental capability, and the projected computational methodology were determined. Development of such a complex program would itself be expected to be complex.

The new program was planned to allow the incorporation of future improvements in modeling in an orderly, controlled manner. If improvements in any one component of the program were generated, then that change could be incorporated without interfering with the remainder of the program. Program control was directed towards tracking changes in the program structure itself as well as in all the component modules. With regard to loads prediction, the program would have the ability to consider blade aerodynamics for either lifting line or lifting surface viewpoints with prescribed or free wakes.

The projected effort is considered to be extensive and amitious. It will attempt to model the entire helicopter in its various flight modes. It is to provide the user with great flexibility. The key to its ultimate utility is the level of quality and configuration control that is actually achieved. The same management attributes will be needed for this program as are found in successful large scale weapons systems programs. To anyone who has written, modified, and used complex computer programs, the thought of a possible missed comma in this comprehensive system must give pause. Verifying and validifying each sub-program and the entire program will require enormous time, funds, patience and stamina. The entire system will be only as good as its ability to correlate with the results of tests.

## 2.4 EXPERIMENTAL CORRELATIONS AND VERIFICATIONS

The papers in this session reviewed correlations between selected mathematical models and data obtained from test. The analytical approach and the test data used to correlate were unique to each presentation.

In the first paper coupled mode shapes were utilized with aerodynamic models that used the acceleration potential model, a simplified Meijer-Drees model, or various vortex models (16). Correlation was made with data from a 3 meter diameter model rotor tested in a wind tunnel. Predicted local thrust variations around the azimuth were compared to measured values for the tip region of the blade. Comparisons showed that the trends were predicted adequately but the magnitudes were not presented as well.

Comparisons were also made between the predictions and flight test data from a Gazelle and a Puma helicopter. The authors concluded that their predictions were fairly good for flapping moment, and not yet acceptable for drag moment. They believed that difficulty existed in the torsion calculation and that the analysis of torsion coupling would have to be improved.

The next paper presented a correlation between results obtained from wind tunnel tests of a hingeless 4 meter diameter rotor and theoretical predictions for the rotor (17). The aerodynamics used in the model included global momentum, local momentum, and a rigid vortex wake. Rotor dynamics were described by a model with fully elastic blades using coupled modes based upon the equations of Houbold-Brooks. Equivalent flapping was determined using a root stiffness factor. Measurements taken in the experimental work included rotor hub forces and moments, blade root moments, and downwash measurements.

The correlation between measured and calculated torque and hub moments due to the sine component of control were considered to be good. The correlation for flapping response due to the sine

input was not considered to be good. Comparisons of analytical and measured time averaged velocities in the wake indicated qualitatively similar results in hover. In forward flight the correlations were generally poor except at large values of rotor shaft tilt where it could be expected that the forward flight velocity component would dominate the wake.

The work reported is a good first step. It attempts to consider the entire problem: analysis, wind tunnel testing, rotor and blade response as well as flow field measurements. It is apparent that added testing will be necessary to obtain more fine-grained data on the various measured quantities such as the airflow, probe positions, and blade and hub characteristics. It would also seem logical to attempt to correlate the data obtained with some of the more sophisticated analytical techniques available.

In the next paper the interaction of a vortex with the following blade was investigated (18). Data were obtained using a Puma aircraft. A large number of pressure pickups had been placed along the leading and trailing edges of one rotor blade. Analysis of the data indicated that in the plan view the intersections of the tip vortex from one blade with the following blade could be predicted quite well using a simple wake model. Likewise the blade-vortex intersection angle could be predicted quite well. The vertical spacing, however, of the vortex with the following blade was not predicted adequately. Since this vertical spacing had to be inferred using measured surface pressure, it would not be unexpected that correlation did not turn out well. The work did, however, present a method of deducing vortex interaction phenomena. As such it could be useful in refining wake-geometry models.

The last paper of this session presented information on DATAMAP, a computer based analysis and flight data retrieval system (19). A large block of data obtained from flight test of an AH-IG helicopter had been stored in magnetic tapes. Two hundred and twenty-four different flight conditions had been run and data from 387 transducers recorded. The paper indicated that the DATAMAP system incorporates the C-81 program, and can be adapted to utilize other analytical programs. The primary features of the system were stated to be the ability to recall and present both analysis programs and data for comparison, the ability to call up data sets from different sources, and the ability to provide a wide range of output formats. The DATAMAP system had acted as a forerunner to the more extensive 2GCHAS system, and many of the features planned for 2GCHAS have evolved from DATAMAP. It was expected that experience acquired with DATAMAP will continue to enhance the development of 2GCHAS.

The DATAMAP system as presented seems to offer a logical way to exploit the mass of data that was obtained in the flight test program. It offers a data base against which other analytical programs can be evaluated, and with the direct comparison mode described in the paper could be utilized to great advantage for code verification.

## 3. EVALUATION

The theme of this Specialist's Meeting was stated as "the prediction and experimental verficiation of the steady and unsteady aerodynamic forces on the rotors of modern helicopters and related devices." This is a concise and directed charter. It implies an intensive review of the fluid mechanics associated with rotors and the interactive response of the rotor to that fluid flow. It specifically delineates prediction and verification, - correlation between an analytical prediction and experimental results. In meeting these ends the meeting was only partially successful. Reviews of the overall flow and rotor dynamic response were made, usually in the context of the status of the development of a large dynamic analysis program. No clear cut review of the status of the knowledge of the detailed nature of the rotor flow field was presented, nor was there a comprehensive review of the nature and status of analytical methods needed to describe the flow field. Neither was the coupled rotor-fuselage flow problem viewed as a whole wherein the detailed aspects could be fit together to form the whole. Rather a whole series of presentations were made on very specific pieces of this puzzle, tip shape, airfoil sections, fuselage proximity and the like.

The modeling of the dynamic response part of the problem left one with a much greater feeling of confidence. The primary thrust here was the adaptation and extension of classical and modern numerical techniques to the problem of helicopter structural modeling. The wide range of forcing functions that can excite rotorcraft response require very precise knowledge of the natural frequencies, damping and possible instabilities. The tools to do this appeared to be relatively well advanced. The major concern related to this area would seem to lie in the need for precise and careful control of the numerical/computer programs used to insure that consistent, reliable, appropriate and verified models are used.

Unfortunately, there was no in-depth discussion of an inherent problem in rotor loads prediction which arises because of the dynamic and aerodynamic response of the rotor to interaction of the rotor and the fuselage. Presentations did cover the aerodynamic interaction between the flow fields about the fuselage and the rotor. Serious concern has existed, however, about the possible feedback of fuselage component flexibility and response into the rotor aerodynamics. Shaft and hub deflections, swash plate deflections, or control system deflection can all introduce pitch inputs to the rotor. These inputs can include higher harmonics as well as nonlinearities. These inputs, though quite small, will affect the forces generated by the blades in a manner similar to those forces produced by higher harmonic control. Systematic study of such coupling actions should be made and one would expect that the comprehensive models developed in the future would incorporate the results.

A word of caution must be expressed about the use of the complex computer models being evolved. Since almost everything and every possiblity conceivable is contained within these large models, it may be as difficult to truly comprehend what the model is telling us as it is difficult for us to comprehend the physics of the actual rotor in its operation. It would seem to be essential to utilize instrumentation so located aboard the aircraft that comparisons can be made between numerical modeling and test. This should be done as now accomplished in the automotive industry where very close interaction between numerical analysis and test evaluation allows rapid diagnosis of specific local problems.

If we return to consider the aerodynamic forcing functions, review of the status of aerodynamics as presented in this meeting revealed that considerable progress has been made on segments of the aerodynamic problem. Development has continued on airfoils. Significant work has been made on non-steady effects near stall and separation. The transonic flows at the tip of the blade have been studied and the models are evolving. Vortex-blade interactions are being modeled although the

ability to predict vortex location is not yet precise and local effects of vortex-airfoil interaction are not known yet. The influence of tip sweep has received extensive study through analysis, wind tunnel test and flight test.

The wake models which were considered included simple momentun, local momentum, rigid vortex, ring vortex, prescribed wakes, circulation coupled, velocity cou ›d, free wakes and acceleration potential based. All these, of course, are approximations to the actual wake. They exhibit a broad range of complexity and required computer time. The wake models are critical to the loads prediction because each wake model produces a unique contribution to the flow field near each rotor blade. That wake induced flow plus the localized contribution of specific vortices, three dimensional tip flow, blade motion and deflections, fuselage influence, and aircraft motion all act to produce the local surface flows and pressure distributions. Because of the critical nature of the wake model, checking its validity with test data is extremely important.

The experimental verification of the various wake models seemed to focus on comparisons made between predicted rotor response characteristics and flight or wind tunnel measurements of the response. In most cases the comparison was made with hub moment, blade bending moment, or local blade thrust at selected spanwise locations. This was particularly true of the more complete and complex analyses.

Little discussion was directed during the meeting towards the correlation of the more complete flow descriptions with flow velocity measurements, a procedure which would allow more direct comparisons to be made. Some new data on rotor flows were presented at the meeting. Time averaged values of velocity at selected azimuth positions and vortex locations had been obtained using hot wires, LDV, and flow visualization in the test of model rotors. However, when comparisons of the data obtained were made with results from analysis, such comparisons usually were made with flow models created explicitly to meet the specific test configurations.

It is recognized that in a closely coupled system, such as a flexible articulate blade operating in a time varying airstream, it is essentially impossible to separate fluid mechanics from the dynamic response. Evaluations which are made of flow models and which are based upon blade-bending stress, root bending moment, or blade-root torsion include the results of the integration of many factors which may obscure details. Therefore, when agreement is claimed to be achieved between the predictions of a flow model and some measured rotor parameter, that agreement may be fortuitous. Also, when corrections are applied to make the models fit the data, there is little certainty that the model can be applied to rotors having any significant parameter change from the rotors used to get the data. Comparisons made of surface pressure calculated using a wake model with test data on surface pressure involve less of this integrating action. Though comparison of pressures is an important technique, it suffers from a lack of certainty of what the airfoil characteristics will be in the local curvilinear non-steady flow field. Implied is the point that we do not know the details of the local field nor do we know how an airfoil will respond to that field.

## 4. CONCLUSIONS

The theme of this AGARD Fluid Mechanics Meeting is considered to be a valid one. Understanding aerodynamic loads remains as a pacing factor in the development of rotorcraft. The meeting did provide for a broad overview of work being done related to the theme area. Many papers, however, presented results of very specific efforts, tip shape for example, that were only peripherally related to the major theme. A few papers presented a broad overview of the status of work on loads prediction. A serious concern remains, however, that the intent of the conference may not have been fully met. The theme clearly called for prediction and verification of that prediction. Few papers presented experimental correlations of the aerodynamic forcing functions that were at a level similar to the extensive models and codes presented. Most of the data used for evaluation were structural response data or were dependent on that response.

Because of the great importance of verification of the analyses and codes, it is concluded that

- Codes and analysis have not been adequately verified
- Adequate data bases for verification are not generally available
- The data bases which have been used generally are not comprehensive and usually lack important information such as flow velocities, pressures, or other measurements taken simultaneously
- Experimental efforts have often been run quite independently of the analytical programs and often do not meet the needs of the programs.

## 5. RECOMMENDATIONS

It is recommended that an intensive review be made of the status of rotorcraft load verification. To conduct such a review, a panel of specialists in analytical and numerical prediction methods and experimentalists knowledgeable in rotor flow and loads measurement should be convened for the purpose of determing:

- What type of verification is needed
- What types of data are needed
- What data are presently available
- What data remain to be obtained
- Priorities for the data
- What types of testing should be run

- model test
- full scale tunnel
- flight test

. The potential impact/limitations of scaling

. The possible data formats

. The need for non-steady data

. The possible utility of and the possible configuration of standardized base line configurations

. The possibility of seeking a future forum in which comparisons are presented between the analytical and numerical prediction models and the standard data base, once such data bases are obtained

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# 7. APPENDIX

## An Approach to Obtain the Needed Data Base for Verification of Flow Models

### INTRODUCTION

As pointed out in the Evaluation, Conclusions and Recommendations Sections in the body of this report, a firm data base does not exist suitable for verification of the various flow models used in the helicopter community. As a possible aid in establishing such a data base, this appendix is written. It offers a possible approach for the acquisition of such a data base.

### APPROACH

It is believed to be imperative that systematic measurements be made of the velocity field in the vicinity of the rotor. Such measurements should be made with the purpose of providing a data base which could be used to evaluate the various models. Initially hover and foward flight conditions at high advance ratio should be run. Any such program would have to be structured carefully since it would involve a massive data handling task. To acquire details of the flow would require the measurement of non-steady 3-D velocities at many selected points in the wake. So much data can be acquired for even the simplest case that interpretation becomes difficult.

To verify any analysis or theory it is essential that the model and the test be as similar as possible. The configuration chosen to work with initially should be as simple as possible and still represent a working rotor. The measurements taken should be comprehensive and include flow visualization of the wake geometry, flow field measurements, blade pressures, blade stresses, torsion moments and rotor loads and moments. Average and time varying data should be taken. All pertinent blade, hub and mounting structural and aerodynamic characteristics should be carefully recorded. The rotor configuration under test could initially be a simple square-tipped model rotor with flap and lag bending and torsion frequencies as high as practical in a model rotor. Initially, tip speeds might be kept to low values so as to reduce the compressibility effects on the advancing blade and the concurrent complexity of blade tip flow modeling and also to reduce the difficulty of modeling the vortex itself and its subsequent interactions at the higher Mach number conditions.

Following work with this base line configuration, discrete changes could be made, typically a high tip Mach number could be run, or a pronounced change in tip shape could be tested. Such clear cut changes would allow the analysts the opportunity to exercise their models with clear differences in the rotor or its operating conditions. To accomplish such a task in a reasonable time and at a reasonable cost such work would probably have to be done with model rotors in wind tunnels, or on hover stands. Although a full-scale rotor such as described in the paper on DATAMAP, a Bell AH-1 rotor, could be used in a large wind tunnel, such a test would tie up a large facility for a very long period of time. Thus, it would appear that model rotor tests would form the dominant approach to obtaining data.

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**14. Abstract**

This report presents a summary and an evaluation of the meetings held to review the status of aerodynamic loads prediction for rotorcraft. The complete text of papers presented at the meeting is contained in AGARD Conference Proceedings No.334, "Prediction of Aerodynamic Loads on Rotorcraft". The meeting was sponsored by the Fluid Dynamics Panel of AGARD and was held at Church House, London, United Kingdom, 17–18 May 1982.

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